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Observations that can unravel the coherent radio emission mechanism in pulsars

Dipanjan Mitra

National Centre for Radio Astrophysics, TIFR, Pune University Campus, Post Bag 3, Ganeshkhind Pune 411007, INDIA

Abstract. Searching for the physical mechanism that can excite the coherent radio emission in pulsars is still an enigmatic problem. A wealth of high quality observations exist, which over the years have been instrumental in putting stringent constraints to pulsar emission models. In this article we will discuss the observational results that strongly suggests that pulsar radio emission is excited by coherent curvature radiation. We will also mention issues that remain to be resolved.

1. Introduction

Magnetospheric coherent radio emission from pulsars consist of a main pulse – which is the most bright structure in the pulse profile and associated with a linear polarization position angle (PPA) swing across the pulse; sometimes an interpulse – which is located 180° away from the main pulse and also associated with a PPA swing; occasionally pre/post-cursor emission which is a highly polarized temporal structure with a flat PPA connected via a bridge to the main pulse but located significantly away from the main pulse and the recently discovered off-pulse emission (Basu et al. 2011) which is like a broad emission component observed in regions where no obvious temporal structures are seen in a pulse profile.

To date there is no self-consistent theory that can explain the overall aspect of pulsar emission. Most theories use that idea that the region around the neutron star is a charge-separated magnetosphere which is “force free”, meaning that the electromagnetic energy is significantly larger than all other inertial, pressure and dissipative forces. The magnetosphere is initially charge starved and supply of charged particles can come from the neutron star or due to pair creation in strong magnetic fields. Subsequently the magnetosphere attains charge neutrality by accelerating particles with density equal to the Goldreich–Julian density. In all models of pulsar radio emission there is general agreement that the radio emission arises due to growth of plasma instabilities in the relativistic plasma streaming along curved magnetic field lines. Such processes in pulsar astrophysics are: cyclotron maser (Kazbegi, Machabeli & Melikidze 1991), two-stream instabilities (Usov 1987; Asseo & Melikidze 1998), collapsing solitons (Weatherall 1998), charged relativistic solitons (Melikidze, Gil & Pataraya 2000, hereafter MGP00; Gil, Lyubarsky & Melikidze 2004, hereafter GLM04) and linear acceleration maser (Melrose 1978).

The aim of this article is to summarize the key observational results that have given or have the possibility of providing constraint on understanding the coherent ra-

dio emission from pulsars. Here we will concentrate on the main pulse emission and will also take the position that the coherent radio emission mechanism is excited by curvature radiation from charged bunches (like solitons). The physical process include formation of a inner vacuum gap (IVG) near the pulsar polar cap where non-stationary spark associated relativistic ($\gamma_p \sim 10^6$) primary particles are generated (Ruderman & Sutherland 1975, hereafter RS75). These particles further radiate in strong magnetic field and the photons thereby produce secondary e^+e^- plasma with $\gamma_s \sim 400$. The two-stream instability in the plasma generates Langmuir plasma waves and the modulational instability of the Langmuir waves leads to the formation of charged solitons which can excite extraordinary (X) and ordinary (O) modes of curvature radiation in the plasma as shown by MGP00 and GLM04. For this process to work, highly non-dipolar surface magnetic field is essential (Gil, Melikidze & Mitra 2002).

2. The Shape of the main pulse emission region

The radio emission from pulsars almost invariably arises from regions of open dipolar field lines. The linear PPA swings for a large number of pulsars are in very good agreement with the rotating-vector model (RVM, Radhakrishnan & Cooke 1969) which predicts the behaviour of the PPA arising from open dipolar field lines. The average PPA in several pulsars have a complex non-RVM behaviour, however they are mostly complicated due to the presence of orthogonal polarization modes (OPM). Single pulse polarization can be used to separate the OPMs after which the RVM is clearly satisfied for the individual modes (Gil & Lyne 1994). The distribution of pulse width with rotation period shows a lower bound which scales with pulsar period as $P^{-0.5}$, which reflects the change of dipolar open field lines due to the changing light cylinder distance. Most pulse profiles have one or many subpulses or components. Detailed phenomenological study of average pulse shape and polarization reveal that the pulsar emission beam has a central core emission (surrounding the magnetic axis, Rankin 1990) with typically two or three nested cones around them (Rankin 1993, Mitra & Deshpande 1999). Each of the cones scales as $P^{-0.5}$ and the observed subpulses are the line of sight cuts across the core or conal regions. The distribution of the subpulse width of the core or cone follow a lower bound $2.4^\circ P^{-0.5}$ (Maciesiak et al. 2012), where 2.4° equals the polar cap size for a 1 second period pulsar and a neutron star with a radius of 10 km. In this core-cone model, it is important to understand that the nested cones are not uniformly illuminated, and hence a given intensity pattern in a pulsar can have significant variation in component intensity, however the location of the components appear to follow the conal structure.

The cone structure in the RS75 model results due to the $E \times B$ drift of plasma columns or “sparks” produced in the IVG. The core emission is the central spark (Gil & Sendyk 2000) while the other sets of sparks populate themselves in the polar cap maintaining a distance between them which is of the order of the vacuum gap height. The sparks themselves have the VG height dimension. While theoretically the formation of the IVG is possible, the physical mechanism of how exactly the sparks populate the polar cap and develop in size is not clear. Nonetheless, if these sparks eventually generates a streaming flow of plasma and can generate coherent radio emission at about 500 km from the neutron star surface, then it is possible to explain the observed subpulse widths and core-cone structure observed in pulsar.

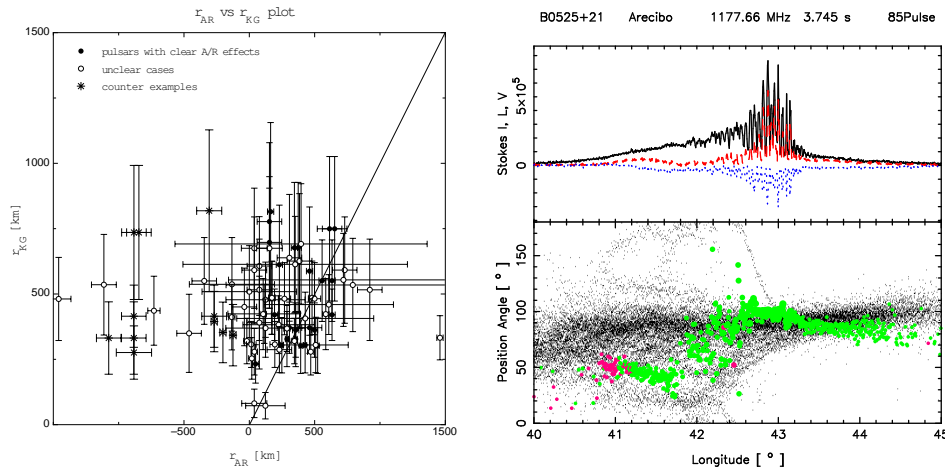


Figure 1. The left figure (adopted from Krzeszowski et al. 2009) shows the comparison between radio emission heights estimated from the geometrical (y-axis) and delay method (x-axis). The conal emission in pulsars is consistent with emission arising at around 500 km (refer Krzeszowski et al. (2009) for details). The right panel shows an Arecibo observation of a single pulse for the 3.7-sec pulsar PSR B0525+21, where microstructure of around 180 μ sec is seen (Backus, Mitra & Rankin 2012, in preparation): a much smaller timescale than the angular beaming timescale of 3 millisecond.

3. The emission height of the main pulse

Two methods of approach have provided emission-height determinations in pulsars, namely the geometrical method and the delay method. In the geometrical method the PPA traverse is used to infer the magnetic axis inclination angle and the line of sight angle, and using the pulse width dimension along with model of the open dipolar field lines, the height can be estimated. The delay method as was suggested by Blaskiewicz et al. (1991) is based on the kinematical effect of aberration and retardation (A/R) and subsequent careful derivation shows that emission heights can be estimated independent of pulsar geometry (see Dyks et al. 2004). The A/R effect is seen as a shift between the center of the total intensity profile and the fiducial plane containing the magnetic and spin axis which is often identified as the steepest gradient point of the PPA traverse or the peak of the core emission. The merits/demerits and usage of the height estimation methods can be found in Mitra & Li (2004) and Dyks et al. (2004). One important point to note here is that the methods mentioned here can only give emission heights for the conal emission region. Determination of core emission height has not been possible to date.

A few notable works dedicated to finding emission heights using the geometrical method are: Rankin (1993), Kijak & Gil (1998) and the delay heights: BCW, von Hoencbroech et al (1999), Malov & Suleimanova (2000), Gangadhara & Gupta (2001), Krzeszowski et al. (2009). The left panel of Fig 1 shows a comparison between the geometrical and delay method by Krzeszowski et al. (2009), where one can clearly see that the emission arises from about 500 km above the neutron star's surface. This finding is a very significant input to the pulsar emission-mechanism problem. The only plasma instability that can grow at these heights (where the magnetic field is very strong

and the plasma is constrained to move along the magnetic field) is the two-stream instability. Hence models like cyclotron maser, which can only give rise to the coherent radio emission near the light cylinder, can be ruled out.

4. Single pulse dynamics of the main pulse

A range of phenomena occurring at different time scales are observed in pulsars. The ones which are intrinsic to the pulsar emission are nulling, moding, drifting and microstructure. In pulsar nulling the radio emission suddenly switches off for time scales as short as a pulsar period up to a few weeks to months. During pulsar moding the average pulse profile suddenly changes from one stable form to another and a given mode can last for intervals of a few minutes to hours. The phenomena of nulling and moding are perhaps the most difficult emission phenomenon to explain and any further discussion on this is beyond the scope of this article.

Pulsar drifting and microstructure phenomena gives indirect hints about the radio loud plasma. Drifting subpulses exhibit drift through the average profile in a very regular manner. In fact for several pulsars very detailed analysis of the observations reveal that a given subpulse seem to have a periodic behaviour which can be modeled as a circular carousel of emitting sparks (e.g. Deshpande and Rankin 2001; Mitra and Rankin 2008), while there are quite a few other pulsars where the carousel timescale can be inferred. In the RS75 model the carousel rotation is explained as $E \times B$ drift of the spark-associated plasma columns in the IVG. However, it is found that the observed timescale of carousel rotation are much longer (several tens of seconds) than the RS75 prediction. A major refinement of this model was given by Gil, Melikidze & Geppert (2006), where the longer carousel rotation time was explained by a partially screened vacuum gap. They also estimated the thermal X-ray emission that arises due to bombardment of charged particles created in the VG onto the neutron star surface. Such thermal X-ray emission has been found in several isolated neutron stars and its connection to carousel rotation is an active area of pulsar research. Additionally, these observations provide direct evidence to the model that an IVGs populated with sparks exist in pulsars.

The pulsar microstructure phenomenon is observed as short time-scale features in the single pulse ranging from 1 to several hundreds of microsec (Cordes 1979; Lange et al. 1998). The microstructure has been thought to reveal either the Lorentz factor of the emitting plasma (Cordes 1979) or are signatures of plasma disturbances (Weatherall 1998). Cordes (1979) finds that the average microstructure timescale (t_μ) scales with pulsar period as $t_\mu \sim 10^{-3}P$. If we assume that pulsar microstructures result due to the angular beaming of relativistic particles, then we obtain a Lorentz factor of around 150 based on the Cordes (1979) relation. We have however ourselves tried to establish this relation but have not been successful so far. We also find that even for very long period pulsars (see Fig 1), in some bright single pulses the microstructure scale is much smaller than the angular beaming time scale. The theory to understand these short timescale temporal effects is still not fully developed. However, microstructures in pulsars are the best examples of the smallest spacial and temporal scale plasma variations producing coherent radio emission. In the IVG model, the microstructures corresponds to spark-associated plasma columns of secondary plasma with Lorentz factors of about 100–500. A large number of such sparks add up incoherently to produce a given pulsar subpulse.

5. Orientation of the escaping waves of the main pulse

Lai et al. (2001) used the x-ray image of the Vela pulsar wind nebula and absolute PPA to establish that the electric vector emanating out of the pulsar is orthogonal to the magnetic field planes, and hence represents the extraordinary (X) mode. This significant observational result for the first time demonstrated that the electric fields emerging from the Vela pulsar magnetosphere are perpendicular to the dipolar magnetic field planes. Lai et al. (2001) also showed that the proper motion direction (PM) of the pulsar is aligned with the rotation axis. Johnston et al. (2005) & Rankin (2007) produced a distribution of $|\text{PM} - \text{absolute PPA}|$ for a few pulsars and found a bimodal distribution around zero and 90° . Assuming that the pulsars PMs are parallel to the rotation axis, the bimodality could be explained as emerging radiation being either parallel or perpendicular to the magnetic field planes, since pulsars are known to have orthogonal polarization modes. Alternatively PMs of pulsars can also be parallel or perpendicular to the rotation axis. While both the above explanations are possible, it is clear that the electric vectors of the waves which detach from the pulsar magnetosphere to reach the observer follow the magnetic field planes. This is in agreement with the IVG class of models where MGP00 and GLM04 demonstrate that curvature radiation can excite the X and O modes in plasma at around 500 km, and the X mode can escape the pulsar magnetosphere almost as in vacuum and reach the observer.

6. Pulsar Polarization and adiabatic walking condition (AWC)

Mitra, Gil & Melikidze (2009) argued that single pulses with close to 100% linear polarization are most suitable for unraveling the pulsar emission mechanism. They showcased highly polarized single pulses from several pulsars where the PPA followed the rotating-vector model. These pulses, which are relatively free from depolarization, must consist exclusively of a single polarization mode which they associate with the X-mode excited by the coherent-curvature radiation. This argument however only holds good if the wave polarization at the generation point in the magnetosphere does not modify as it propagates in the magnetosphere. Cheng & Ruderman (1979) argued that if the AWC (which is given by $|\Delta N|kl \gg 1$, where ΔN is the difference in index of refraction $N = ck/\omega$ between the X and O modes) is satisfied, then the wave polarization slowly rotates, and hence as the wave detaches from the magnetosphere, it no longer carries information about the generation point. However, based on a rigorous treatment of the radiation mechanism GML04 and Melikidze, Mitra & Gil (2012 in preparation) argue that the AWC does not hold in the pulsar magnetosphere and hence the X-mode can escape the pulsar magnetosphere unaffected.

There are two aspects of pulsar polarization which are difficult to understand. One is the existence of OPMs where both the X and O modes are present. Most theories predict that the O-mode should be damped in the magnetosphere. How it escapes is still a puzzle to be solved. The second issue regards circular polarization. If the emission results from incoherent addition of smaller coherently emitting units, then one does not expect any phase relation between parallel and perpendicular electric fields and hence the circular polarization should vanish. Often propagation effects are invoked to explain circular polarization, however these explanations ignore a wide range of other phenomenon, and we feel that currently there is no good explanation for the circular polarization behaviour in pulsars.

7. Summary

The formation of IVG leading to radio emission excited by coherent-curvature radiation is by far the most successful theory that explains the main pulse emission phenomena. Currently challenging simultaneous X-ray and radio observations are being done to understand the IVG conditions in pulsars. We are still uncertain about the origin of pre/post-cursor and off-pulse emission in pulsars. More observations are needed to search and characterize such emission. It is possible that different coherent radio emission mechanisms are responsible for such emission.

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